4.2 Passive-Neutron Calibration

The passive-neutron detector response has not been calibrated and is reported as dead-time corrected count rate (c/s).

Since there is no field verifier for this tool, performance is based on response observed from spectra collected adjacent to the neutron source in the moisture tool before and after log surveys are acquired, and from monitoring the data while logging progresses.

The passive-neutron log data is used to detect fissionable radionuclides in the area of the borehole and is used as a basis for correcting the neutron-moisture survey data for background neutron sources in the waste.

4.3 Spectral-Gamma

4.3.1 Calibration Models

The HPGe detectors are calibrated annually in borehole spectral-gamma ray models located on the Hanford Site. The calibration models are traceable to NIST standards. Data collected in these models permit measuring radionuclide concentrations in formation and waste materials through which the wells or boreholes penetrate. The accuracy of the borehole survey concentrations depend on five factors: (1) the precision and accuracy of the calibration models, (2) the statistical precision of the survey data, (3) the correction of the survey data to match the borehole and formation conditions in the calibration models, (4) the extrapolation from calibration model concentrations to possibly higher concentrations at the field conditions, and (5) the similarity between the distribution of the radionuclides in the calibration models (homogeneous) to the field logging conditions.

The correction of the survey data to match the conditions of the calibration model has been established through analytical measurements. Data were collected in calibration models with various steel casing thickness, and in calibration models with various hole sizes for establishing casing and water corrections, respectively (Koizumi et.al. 1992).

The Hanford spectral-gamma ray calibration models were constructed at the U.S. D.O.E. facility in Grand Junction, Colorado, and are steel tank enclosures with zones of ordinary (barren) concrete separating enriched concrete zones with high radionuclide concentrations. The tanks are 4 ft in diameter and about 22 ft high, and are buried below ground surface. Each calibration tank has two enriched zones that are 4 ft thick and are separated by a 5-ft thick barren zone. The tanks have an uncased borehole through the center and it extends (as a cased hole) below the tank (into the ground) for accommodating logging tools that have a detector located high in the probe housing. The calibration model hole size is 4.5 in. Figure 7 shows a schematic of the calibration model design.

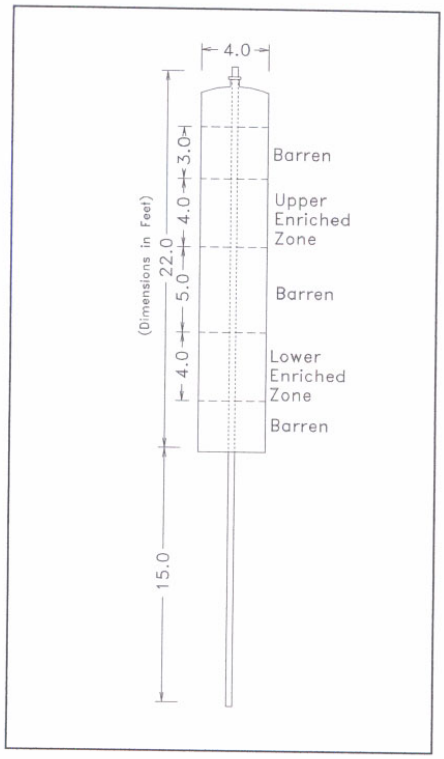

Figure 7 Cross-Section of a Hanford Gamma Calibration Model

The models are filled with water to keep the concrete saturated, and to maintain equilibrium of the radioactive decay chains containing radon gas, which can migrate out of the model. Studies conducted by C. J. Koizumi, phD (1993) showed that dry storage of the models for three years prior to installation at Hanford did not affect the radionuclide concentrations or the integrity of the calibration models.

During calibration, the water in the models is temporarily pumped out, allowing the calibration log to be acquired in dry boreholes. Two of the calibration models (top of access casing) are shown in Figure 8 along with the covered moisture models.

Three zones in the two models have enhanced concentrations of potassium, uranium, or thorium, and a forth zone is enhanced with a mixture of all three of these natural radionuclides. Two enhanced zones are present in each borehole calibration model and are designated as SBT/SBK and SBU/SBM. The radionuclide concentrations are summarized in Table 3.

Table 3 also lists the densities of the calibration models as dry bulk constituents (water removed) and the partial density from water.

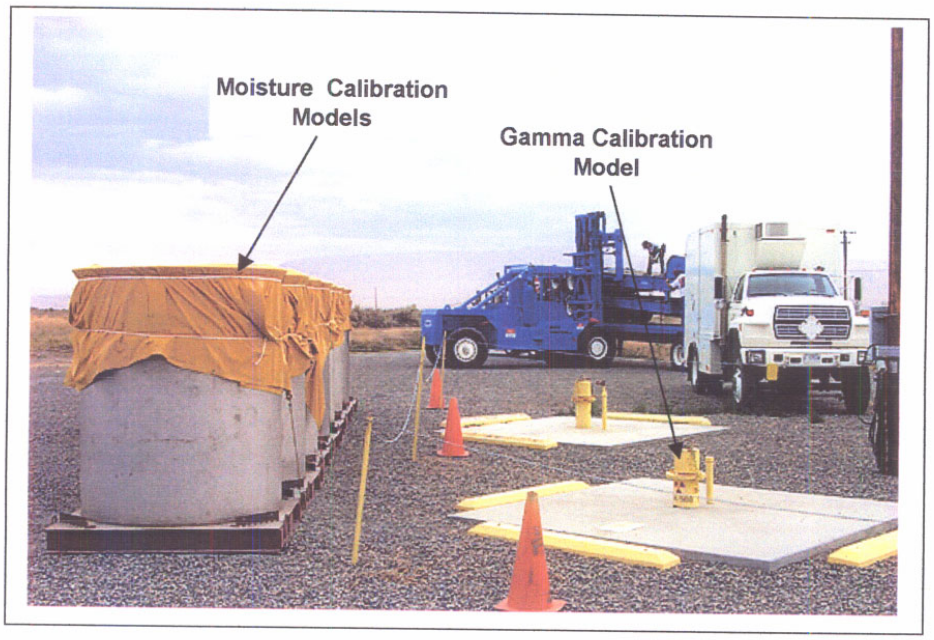

Figure 8 Hanford Moisture and Gamma Calibration Models

Table 3 Gamma Calibration Model Concentrations

Model	Zone	Depth (ft)	Concentration * (pCi/g) ^{40}K	^{226}Ra	^{232}Th	Dry bulk density (g/cm^3)	Partial density H_2O (g/cm^3)
SBT	Th	6.5-10.5	10.6 ± 1.3	10.0 ± 0.5	58.1 ± 1.4	1.92	0.233
SBK	K	15.5-19.5	53.5 ± 1.7	1.16 ± 0.11	0.11 ± 0.02	1.82	0.246
SBU	U	6.5-10.5	10.7 ± 0.8	191 ± 6	0.66 ± 0.06	1.90	0.240
SBM	Mix	15.5-19.5	41.8 ± 1.8	126 ± 4	39.1 ± 1.1	1.87	0.251

*Uncertainties are 95 percent confidence interval (2 sigma)

The concentrations are specified as pico-curie (pCi) of the radionuclide per gram (g) of model mass and are traceable to NIST gamma-ray counting standards certified by the New Brunswick Laboratory at Argonne, Illinois (Trahey et al. 1982a; Trahey et a. 1982b; Steele and George 1986).

The natural uranium concentration is reported as radium-226 (^{226}Ra) instead of uranium. In the uranium decay chain most of the gamma rays come from the daughter products of uranium that are in secular equilibrium with ^{226}Ra. When ^{226}Ra is in secular equilibrium with ^{238}U (as it is in the calibration models), both ^{226}Ra and ^{238}U have the same concentration in terms of pCi/g.

The concentrations of the calibration models were originally specified in units of weight fraction (weight of radionuclide per weight of the model, ppm) but were converted to pCi/g. This conversion eliminates the requirement for density correcting the survey data to match the calibration models.

These corrections would be difficult since formation densities vary with depth and it is often difficult to obtain density data for boreholes and wells since this information is not routinely collected. The factors utilized for the conversion are presented in Stromswold 1994.

4.3.2 Spectral-Gamma Calibration

Calibration of the spectral-gamma logging tools is performed annually and a calibration certificate is issued for each tool; copies of the certificates are maintained in the logging vehicle as well as with Hanford document control. For the RWMC logging, only the 35 percent efficient passive HPGe detector requires a calibration certificate, as discussed below. The 20 percent HPGe n-Gamma detector is calibrated for chlorine only and the calibration of this tool is discussed in Section 4.4.1.

Calibration is performed with the HPGe detector centered in each of the enriched zones of the calibration models. When positioned in this manner, the measurement geometry is such that the radioactive zone appears as an infinitely thick homogenous zone to the detector. Measurements are acquired at a minimum in the SBU (uranium) and SBT (thorium) calibration zones. The energy dependent efficiency function for the detector is established from the measured gamma ray peak count rates, the calibration model concentrations, and gamma rays per nuclear decay of each radionuclide. When these calibration points are fitted by an appropriate function, any measured gamma ray count rate, regardless of energy (provided it falls within the energy range of the fitted calibration data), can be converted to gamma activity (concentration).

The conversion of count rate to concentration requires knowledge of the number of gamma rays emitted per 100 decays of the radionuclide of interest. For example, the 414 keV gamma ray emitted from the decay of ^{239}Pu is emitted with an intensity of 1.51E-3 gammas per 100 decays. The conversion or calibration is given by:

$$C = \frac{\varepsilon(E) \cdot P}{N}$$

Where:

C is the radionuclide concentration in pCi/g by dry bulk mass,

ε(E) is the energy dependent efficiency function obtained from the calibration data,

P is the corrected net peak count rate in c/s (corrected for dead-time, casing density and thickness), and

N is the number of gammas emitted per 100 decays.

The calibration function for the 35 percent efficient HPGe logging tool (RLSG035A00S00.0) on the INEEL logging unit (August 2000) is given by:

$$\varepsilon(E) = (8.385 \cdot E^{.238}) + (1.01 \cdot 10^{10} \cdot E^{-4.301})$$

E is the gamma ray energy in keV, and the constants are the results of fitting a function of the form ($aE^{\alpha} + bE^{\beta}$) to the measured calibration data. The units for the efficiency function are c/s divided by (gammas/100 decays x pCi/g).

The function ε(E) is valid in the range from 75 keV to 3,000 keV. Special considerations are required to analysis at energies below 300 keV, due to photoelectric effects in unknown formation conditions.

In addition to the annual calibration of the spectral-gamma logging tools, performance of the tool and ancillary logging instrumentation is verified daily in the field before and after log data are acquired. This is accomplished utilizing an Amersham field verifier, which is a stable source that emits a spectra with several gamma ray energies from a mixture of potassium, uranium, and thorium. Spectra are recorded with the tool placed at a consistent position within the cylindrical-shaped verifier, and these spectra are analyzed to determine the energy resolution and to assess system gain drift. Additional spectra are recorded with the tool outside of the verifier to measure the background activity in the vicinity of the tool and verifier. The verification process is described in detail in WMTS-OEM-001, Section 17.0, Attachments D and G.

4.4 Neutron-Capture / Spectral-Gamma

The dominant elements occurring in the natural formation material, steel cased borehole, and Rocky Flats waste targeted by the n-Gamma tool are listed in Table 4. The signature gamma ray energy processed by the analysis program for each element is included in the table. The chemical composition or mixtures of the elements identified with the n-Gamma logging tool are not identified.

Table 4 Dominant Elements Detected by the n-Gamma Tool

Element symbol	Element Name	Gamma Ray Energy (keV)	Natural source in formation materials or in drilling materials	Possible source in waste
H	Hydrogen	2223	H2O; water	Lubricating Oils
Si	Silicon	3539	SiO_2; silt, sand, basalt	Calcium silicate
Ca	Calcium	3907	$CaCO_3$; calcareous cement, lime	Portland Cement
Fe	Iron	6018	Steel casing	Drums, metallic debris
Cl	Chlorine	1165	(negligible in native soils)	Chlorinated solvents, organic compounds, chlorinated salts

4.4.1 Calibration in Minimum Threshold Detection Model

The neutron-capture / spectral-gamma (n-Gamma) logging tool has been calibrated in a steel cased borehole for chlorine (as a uniformly distributed source) in a concrete model with a thin zone of chlorine. The minimum detection level for this tool in the threshold detection model for chlorine is 300 ppm.

The minimum detection levels for chlorine was determined for the n-Gamma probe by measurements acquired in the "Contaminant Detection Threshold Model". This model was relocated in 1998 to the Hanford Site from the U.S. DOE Office in Grand Junction, Colorado.

The model is constructed of concrete with a 6-in. thick contaminant-doped disk sandwiched (vertically) between 2.75-ft. thick concrete disks of contaminant-free zones (Wilson, 1994). The disks and cylinders have a 6-in. diameter borehole through the center for logging tool access. The 6-ft high stack of cylinders (upper barren disk, contaminant disk, lower barren disk) with a diameter of 2 ft, are placed in a 7 ft diameter steel tank. The region between the tank wall and outside of the concrete cylinders is filled with pea gravel.

Several contaminant-doped disks have been constructed and can be placed, one at a time, between the upper and lower barren disks for logging measurement. The inventory of disks includes: chlorine, mercury, cadmium, samarium, and gadolinium. There are two disks containing chlorine. One chlorine disk contains 1.4 wt percent. The other chlorine disk has 0.28 wt percent and has boron carbide added to match the macroscopic thermal neutron capture cross-section of the high concentration disk and the contaminant-free disks (which also contain boron carbide). This was done to produce a model with uniform neutron and gamma transport properties. The cylinders are removable and only one contaminant disk can be accommodated at a time.

The calibration model with the small contaminant-doped disk (6-inch thick by 2-ft diameter) does not appear to the logging tool as an infinite zone. However, special processing of the calibration data permits an appropriate calibration factor to be produced.

Since the model was designed to have uniform neutron and gamma ray transport properties (for 6-ft diameter by 7-ft high), measurements made at 0.5 ft intervals over sufficient depth range above and below the contamination zone will produce the uniformly distributed contaminant response when all measurements are summed.

4.4.2 Calibration in High Chlorine Concentration Model

As requested by INEEL, the response of the n-Gamma tool was characterized (August 2000) in a borehole model containing steel casing (thickness identical to RWMC boreholes, 0.50 in), water (de-ionized), and variable amounts of chlorine (salt, NaCl). The study demonstrated that the chlorine net peak count rate did not increase proportionally with increasing chlorine concentrations. Also, as the amount of a neutron absorber (chlorine in the salt) was added to the model, the percentage of thermal neutrons captured by the constant components of the borehole model (hydrogen in the water, and iron in the steel casing) was decreased. The saltwater tank calibration data confirm self-absorption by chlorine and the non-linear relationship between chlorine concentration and detector response.

Results of the characterization (saltwater calibration) study were used to validate a computer modeling code (MCNP) which permitted the computer code to be used to calculate the probe response for different configurations, minimizing the need for additional calibration models. The results of the borehole model measurements and MCNP modeling (documented in Appendix B) are summarized below.

Comparison of the maximum chlorine responses measured in the available SDA study area boreholes with the saltwater calibration function showed several boreholes with much higher responses than can be possible with the calibration function. The saltwater calibration function does not exist for

chlorine (1165 keV) photo peak count rates greater than 12.39 c/s. Over twenty SDA boreholes were identified with chlorine count rates greater than 15 c/s. The range of chlorine and hydrogen photo peak count rates in these high chlorine boreholes is 16-38 c/s for chlorine and 4-26 c/s for hydrogen.

Parameters in the MCNP computer modeling code for the salt-water borehole model were replaced and the program was re-run with the properties of the dominant chlorine based Rocky Flats waste buried in the SDA (743 series sludge, with carbon tetrachloride). The maximum permissible count rate activity for 743 sludge increased significantly, from 12.4 to 17 c/s, but remained far below the values measured in most borehole surveys with high chlorine content.

Several borehole surveys with high chlorine responses have low hydrogen responses. Low hydrogen responses in the waste indicate lower moisture content than is present in the saltwater calibration tank. Since the high hydrogen concentration in the saltwater calibration tank results in a smaller diameter thermal neutron cloud there is correspondingly a smaller chlorine signal. To demonstrate how the amount of hydrogen present in the soil influences the thermal neutron flux density (neutron cloud size) the MCNP code for the saltwater tank was run with 25% of the original hydrogen content to permit a larger, more realistic thermal neutron cloud. The maximum chlorine response increased significantly from 12.4 to 23.6 c/s; the hydrogen response decreased from 8 to 4 c/s. The comparison of these predicted values (24 c/s and 4 c/s for chlorine and hydrogen, respectively) with the SDA boreholes having high chlorine survey responses showed that all of the boreholes with low hydrogen responses had chlorine responses that were within the predicted range.

Examination of the logs for several boreholes (e.g. borehole P903) with high chlorine shows that the contamination distribution profile is more characteristic of a thin zone than for a thick uniform interval of chlorine waste. Hence, a MCNP modeling scenario for a thin zone of high concentration chlorine waste was processed. The thin zone is 10 cm thick of 743 sludge at maximum concentration estimated by INEEL and the material above and below the thin zone is similar to soil material with water content of 15% by volume. The maximum response predicted for chlorine and hydrogen by the MCNP code is 32.4 and 13.8 c/s, respectively. The comparison of these predicted values with the high chlorine SDA boreholes showed that almost all of the remaining surveys had responses less than these values.

The match between the MCNP results summarized above (details in Appendix B) and the borehole log data should not be interpreted as validation of the configuration of subsurface waste. Other non-uniform configuration sets of waste can possibly be constructed that may yield comparable results. However, the modeling discussed here does indicate the direction and magnitude that lumped concentrations of waste can have on the instrument response.

Since the calibration function from neither the salt-water calibration model nor the 743 sludge properties can be used to compute chlorine concentrations, the elements (chlorine, hydrogen, silicon, calcium, and iron) identified in the n-Gamma survey are reported in net peak count rate. After an appropriate calibration is established for chlorine, reprocessing the survey results to compute concentrations can be readily performed.

The response of the nGamma logging tool is affected by formation conditions that change the neutron flux cloud (such as the presence of neutron absorbers, voids in the waste materials, changes in moisture content, and density variations in the pit waste). The borehole surveys do not include measurements to quantify the changes in the neutron flux cloud; therefore, there have been no corrections to n-Gamma data for formation environment conditions.

4.4.3 Modeling

Computer simulations were performed with the Monte Carlo code (MCNP) in support of the RWMC logging. The computer calculations that were performed fell into two basic categories. First, calculations were used to support the mechanical design of the logging tool. Second, MCNP calculations were used to extend the calibration range of the tool and to assist in the interpretation of the logging tool response. The goals and objectives of the calculations that were performed are described below. The details of the models and results are contained in the report titled "Radiation Modeling in Support of INEEL Pit 9 Borehole Logging", a copy of which is included in Kos, et.al. 2000.

The initial MCNP modeling was involved with determining the mechanical design of the logging tool. Selection of the optimum source-to-detector spacing is critical to the instrument response to soil conditions surrounding the logging. At the optimum source-to-detector spacing, the logging tool would respond to the chlorine signal independent of the soil moisture content over the range from 5% to 20% by volume. Therefore, the chlorine capture gamma ray signal would not require significant correction for differences in moisture content between the materials in the calibration models and materials expected to be present at the RWMC study areas.

Simulations were performed to predict the response of the chlorine signal to the various soil and borehole conditions and formation properties. The simulations were performed to (1) determine the borehole size and casing thickness factors for the chlorine logs; (2) evaluate the effects of formation density and moisture content on the n-Gamma logging tool response; (3) determine the effect of thermal neutron cross-section on tool response; and (4) predict the capture gamma count rates from a radially remote chlorine distribution (i.e. point source).

MCNP calculations were benchmarked by data collected in both the moisture calibration standards and the chlorine calibration standards (concrete disk model, February 1999, and salt-water tank, August 2000) that are located at the Hanford Site calibration facilities.

The February 1999 calibration data were collected in physical models constructed by Grand Junction DOE, (as described in Section 4.4.1). The chlorine models are thin cement disks with 6-in. inside diameter borehole through which a casing with 0.5-inch wall thickness was inserted. MCNP calculations were utilized to extrapolate from the physical conditions of the calibration model to the RWMC boreholes and expected soil conditions. These extrapolations were based on the following conditions:

- A 0.5-in difference in borehole diameter (i.e. casing outside diameter of 5.5-in and borehole diameter of 6-in.)
- A sand versus cement matrix containing the chlorine waste.
- The difference in moisture content from the cement model (high moisture) to expected 5% moisture content for RWMC conditions.
- The difference in capture cross-section between the boron enriched cement of the calibration model and the nominal sand fill for RWMC conditions. (note, nominal sand fill conditions yield lower chlorine detection threshold values)
- The changes from the concrete model density to expected density for the RWMC conditions

All calibrations are derived for uniform distribution of materials surrounding the borehole. The expected RWMC conditions are non-uniform distributions. Measurements acquired in non-uniform conditions yield responses that could be generated by many other possible non-uniform configurations that produce the same response. It is, therefore, not possible to make corrections for non-uniform distributions without additional information. To simulate a possible waste distribution, MCNP calculations were performed that show the chlorine capture gamma response to a 1 kg "lump" of chlorine that was located radially remote from the borehole at selected distances. The capture gamma responses indicated changes of several orders of magnitude between the chlorine located near the borehole to that located at a distance of 20 in.

MCNP modeling is a valuable tool for characterizing nuclear logging systems and predicting log responses for a large number of subsurface conditions, generally without the cost of constructing additional calibration models.

5.0 PROCESSING TOOL RESPONSES

Borehole survey data for all logging tools are saved on the computer disk as spectra files, with one file for each survey depth position. The spectra files are in the ORTEC pulse height analyzer (PHA) format. The processing method for the data acquired with each tool is described below.

5.1 Neutron-Moisture Data Processing

Neutron-moisture data processing is performed by using the total count rate (dead-time corrected) from the neutron detector as input to the equations defined in Section 4.1.2. The dead-time corrected total count rate is computed by summing all channel counts in a spectra file and dividing the resultant by the Live Time.

The data processing equations correct the detector response for the background neutron activity of the waste (based on passive neutron survey), formation density (constant for all borehole depths), casing thickness, hole size, and compute the formation moisture content in volume fraction percent (vf %). The RWMC borehole surveys do not include measurements to quantify the changes in the neutron flux cloud; therefore, the moisture response has not been corrected for conditions that change the neutron flux cloud, such as voids, neutron absorbers, and variations in bulk density.

5.2 Passive-Neutron Processing

The passive-neutron detector response is reported as dead-time corrected count rate (c/s). The detector signal pulses are tallied into a 500 channel MCA spectra, with one spectra acquired at each measurement position (0.5 ft). An example of the passive-neutron spectra from an RWMC study area is shown in Figure 9.

5.3 Spectral-Gamma Data Processing

Spectral-gamma Data processing is a multiple step algorithm that begins with identifying the main high-energy signature photo peaks for each of the naturally occurring radionuclides (potassium, uranium, and thorium) and evaluating their apparent energy location in the spectra. This operation

is performed to determine if an adjustment of the channel to gamma ray energy conversion factor is required. Adjustments to the channel conversion factor are performed to assign the gamma ray energy to the photo peaks in the spectra, which does not effect the measured concentration. Minor adjustments to the gain are required for several hours after electrical power is applied to the logging tool. Also, since tool power must be disconnected to fill the detector dewar, there is always a possible need for minor adjustments to the channel to energy conversion factor when the tool is reconnected and power is applied.

The second step in the data processing algorithm is to scan the spectra to identify and compute the net count rate and uncertainty of all photo peaks. An example of the HPGe gamma ray spectra from an RWMC study area is shown in Figure 10, and several gamma ray photo peaks are labeled in the figure. The net area in the gamma ray peak is computed as the difference between the total channel counts (defining the peak) minus the continuum background counts (for the same channels). The continuum background counts are computed as the average of the background from the channels above and below the gamma ray peak.

The third step is to match the photo peaks found in the spectra file with the radionuclides and gamma rays selected by the log analyst for analysis. Photo peaks that are not matched to any of specified radionuclides are flagged and a significant occurrence of flagged photo peaks may indicate the presence of additional or unanticipated radionuclides. Spectra with flagged photo peaks are investigated, and adjustments to the radionuclide library are made if the presence of additional radionuclide(s) is confirmed. The second step of the data analysis processing is then repeated to compute the net count rate and uncertainty for the additional radionuclides.

Photo peaks in the borehole survey spectra file that match radionuclide gamma rays are processed through the following equations to compute the radionuclide concentration. The output of the spectra analysis software program is radionuclide concentration (pCi/g or nCi/g) and uncertainty (1 sigma %) in tabular numerical format for each survey depth position.

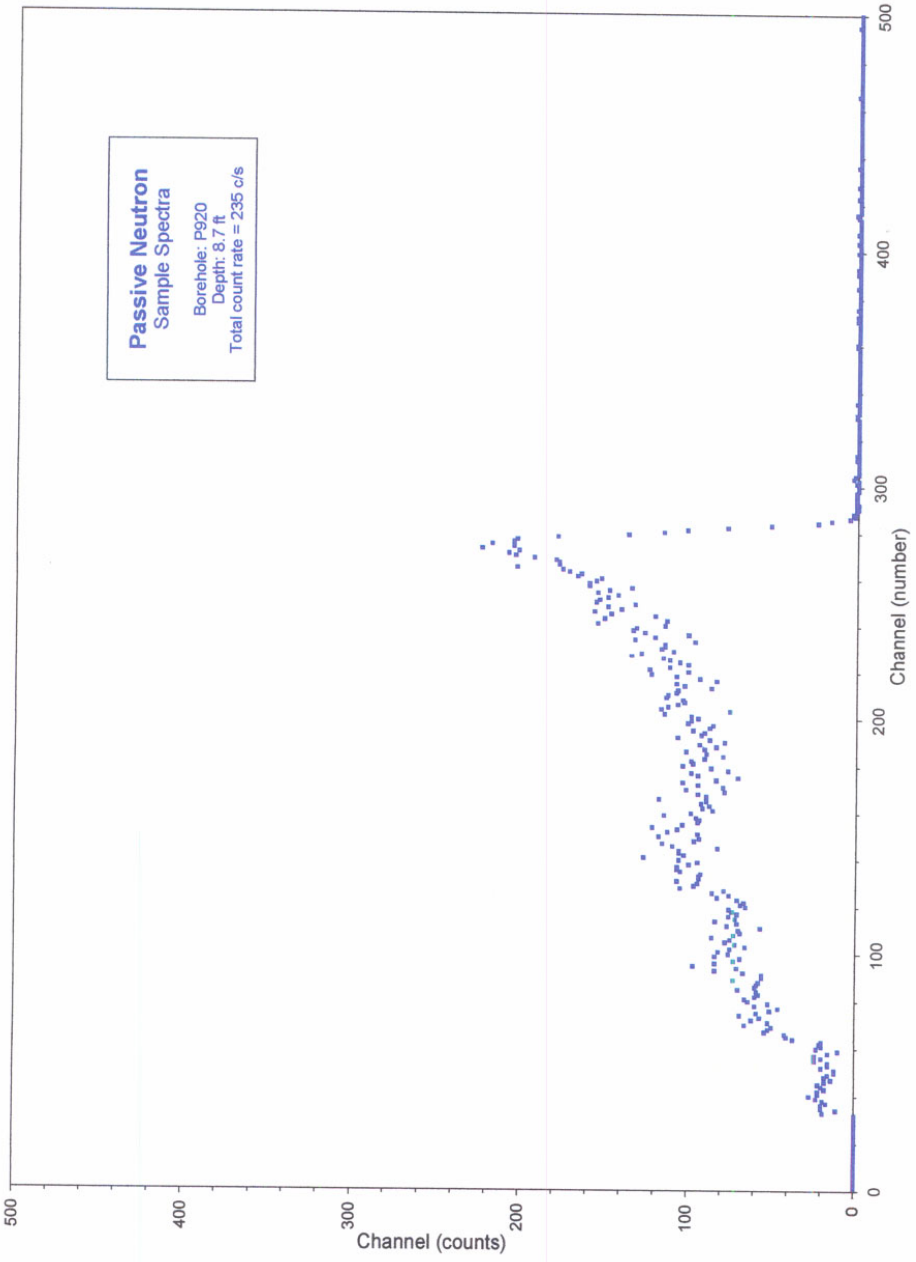

Figure 9 Example of a Passive-Neutron Spectrum

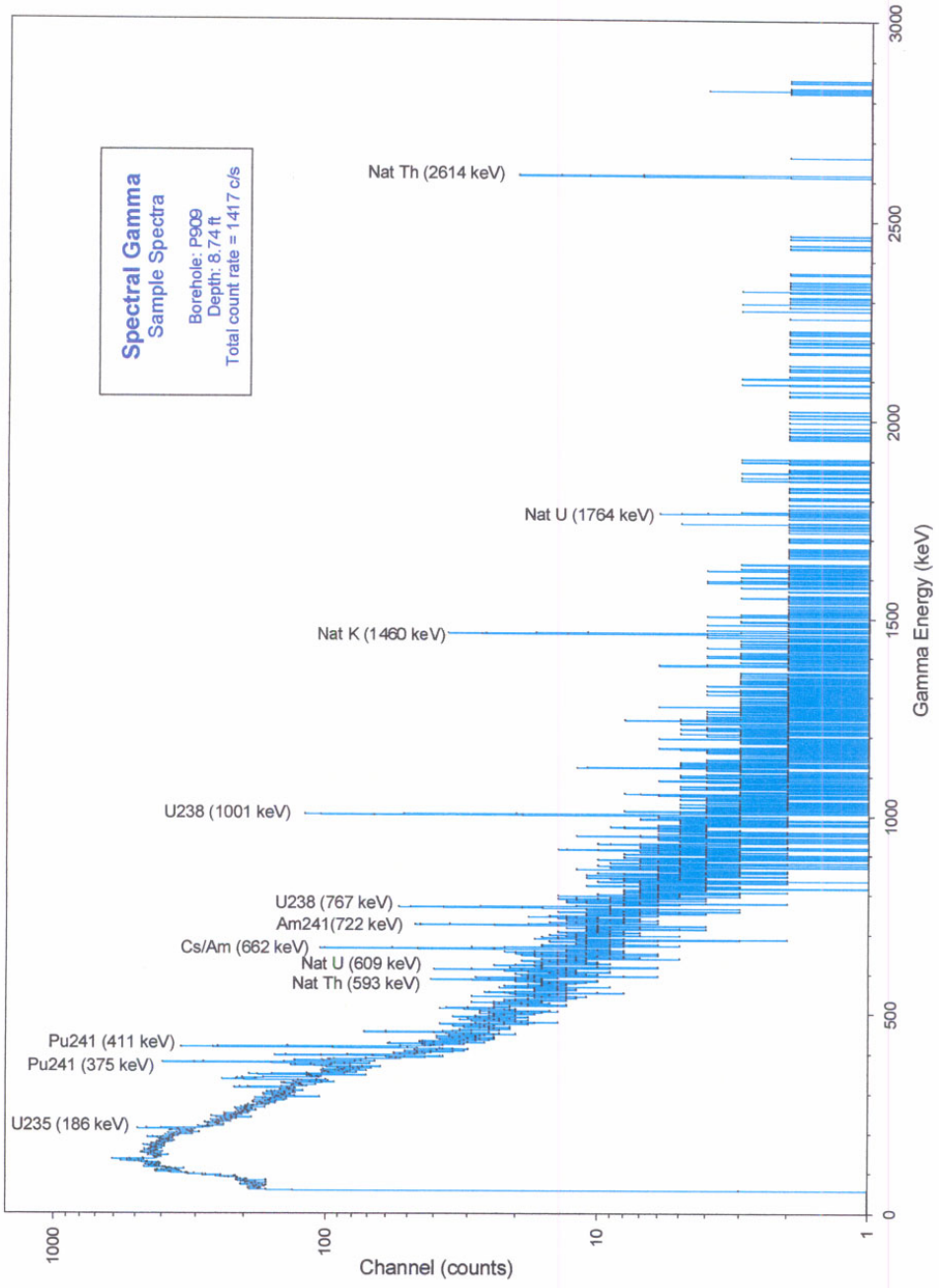

Figure 10 Example of a HPGe Gamma Ray Spectrum

The photo peak count rate is corrected for the casing attenuation utilizing the following equation:

$$P = R \cdot f_{csg}$$

Where:

R is the dead-time corrected net peak count rate from the survey spectra (c/s),

f_{csg} is the casing attenuation factor (see below), and

P is the net peak count rate corrected for dead-time and casing thickness.

The net counts are the counts in the photo peak that are above Compton background. The dead-time conversion is calculated by dividing the net photo peak count rate by the live (counting) time. The casing attenuation factor, f_{csg}, is determined from the following equation:

$$f_{csg} = e^{\mu \cdot p_e \cdot t}$$

Where:

e is the mathematical constant (approximately 2.718282)

μ is the electron attenuation factor (see below),

p_e is the electron density (see below), and

t is the casing thickness (inch).

The attenuation coefficient is determined from the following equation:

$$\mu = k \cdot E^{\kappa}$$

Where:

E is a specific gamma ray energy (keV),

k and κ have been determined experimentally for the borehole geometry to be:

k = 4.584, and

κ = -.46292.

The electron density, p_e, is computed by multiplying the mass density by the 2Z/A ratio for the composite material in the borehole casing. Steel casing has an electron density of 7.325 g/cm^3. Since the peak being processed is the net photo peak count rate it contains only full energy (uncollided) gamma rays which makes this correction rigorous.

The conversion from the fully corrected net photo peak count rate, P, to radionuclide concentration is accomplished by the following equation:

$$C = \frac{\varepsilon(E) \cdot P}{N}$$

Where:

P is the net photo peak count rate (counts per second), corrected for dead time, casing thickness and casing density,

ε(E) is the efficiency function for a specific HPGe detector at specific gamma ray energy (E) in keV (pCi/g per c/s),

N is the absolute intensity (number of gamma rays per 100 disintegrations) of a specific radionuclide gamma ray, and

C is the computed radionuclide concentration (pCi/g).

The efficiency function is defined in the following equation:

$$\varepsilon(E) = a \cdot E^{\alpha} + b \cdot E^{\beta}$$

Where:

a, α, b, β, are fit coefficients obtained during analysis of calibration data. The values of b and β are generally set to zero since they are used for very special conditions that are not applicable to thick wall steel cased boreholes.

During data processing, the statistical uncertainty in the radionuclide concentration in 1 sigma (percent) is calculated for each photo peak processed for each sample interval. Details regarding the calculation of the uncertainty are discussed in WMTS-OEM-001, Section 18.0, Rev. 0, Attachment B.

This sequence of calculations is performed utilizing the software program LGCALC, which was developed for analysis of borehole surveys using HPGe detectors. The software was developed by Westinghouse Hanford Company (WHC) Geophysics Group for use at Hanford; it was independently verified by PNNL (Stromswold 1993). Details of the data analysis process are described in WMTS-OEM-001, Section 18.0, Rev. 0. The mixed units of the data processing equations were developed for ease of use to convert field measurements to applicable radionuclide concentrations.

5.3.1 Detection Limits

Both the minimum detection limits and the maximum system count rate limit for acquiring accurate and repeatable measurements are discussed in the following.

The minimum detection limit (MDL) for the spectral-gamma logging tool can not be given as a generic value because several borehole and formation conditions effect the MDL. These conditions

can change for each borehole survey and actually do change at each measurement location within a borehole. The conditions that affect the MDL of a radionuclide are:

- Detector efficiency (detector diameter-to-length aspect ratio and detector volume)
- Data collection time
- Gamma ray energy used to compute radionuclide concentration and its absolute efficiency
- Casing thickness (gamma ray attenuation)
- Water inside the borehole (gamma ray attenuation)
- Compton background level from all of the radionuclides present in the formation soils

The variable nature of the types of radionuclides that may be present in the formation soils and the large dynamic range of their concentration is the reason that the Compton background level varies and the MDL values are given for a specific condition.

Since many survey measurement locations (depth intervals) in a borehole frequently contain no photo peaks other than the naturally occurring radionuclides a restricted definition of the MDL condition is being used.

> Non-Detect Limit (NDL) is defined as a sub-set to the MDL for a radionuclide under the same conditions that effect the MDL value with one exception. The exception is that the formation soils contain only the natural radionuclides (KUT) at average concentration levels for the zone of interest and no other man-made radionuclides are present. The non-detect level is the maximum concentration of a radionuclide (in an otherwise clean environment) that can be present without a statistically significant photo peak being identified in the spectra.

The reason for the two detection limits is that the non-detect limit (NDL) has fewer variables affecting the result and the associated values are the lowest detectable contaminant levels that represent the waste site. The MDL values, on the other hand, vary with the number of radionuclides present and as their relative concentrations vary.

5.3.1.1 Non-Detect Limit

The general specifications for the non-detect limit for typical RWMC spectral-gamma surveys are given in the table below.

Table 5 Non-Detect Limit for RWMC Spectral-gamma Surveys

NDL Conditions	Value
Detector efficiency	35% HPGe
Spectra Collection time	100 sec
Casing Thickness (carbon steel)	0.5 inch
Water inside borehole	None

The non-detection limit is determined for a radionuclide gamma ray by computing the number of counts that would be required in the photo peak for it to be statistically significant over the Compton background in the energy region of the gamma ray. The non-detect limit is computed the same as the MDL, which is described in WMTS-OEM-001, Section 18.0, Rev. 0.

The Compton background values for the natural KUT radionuclides are separated into three sub-groups in each borehole in the RWMC study area, the overburden, the waste zone, and the underburden. (Note: some RWMC boreholes do not penetrate into the underburden.)

Table 6 contains the results from actual spectra collected in a typical RWMC borehole (P911) for each radionuclide encountered, along with the gamma ray energy (increasing order), number of gamma rays per 100 decays (Intensity), and conversion factor for the 35% HPGe detector from net photo peak count rate to the radionuclide concentration. The borehole contains clean spectra (no man-made radionuclides) in all three zones, and the non-detect limit for each listed radionuclide is provided for the three identified conditions (e.g. overburden, waste zone, and underburden).

Table 6. Non-Detect Limit of Radionuclides for Typical RWMC Borehole.

Radionuclide	Gamma Ray (keV)	Intensity[1] (%)	Conversion Factor[2]	Overburden 2.0 ft	Waste Zone 6.5 ft	Underburden 11.5 ft
U-235	186	54	2.601	1.8 pCi/g	2.0 pCi/g	1.9 pCi/g
Pa-233	312	33.7	3.354	1.7 pCi/g	1.9 pCi/g	1.9 pCi/g
Pu-239	414	1.5	68.84[3]	27.2 nCi/g	29.7 nCi/g	29.9 nCi/g
Natural[4] Uranium	609	46.1	2.038	0.6 pCi/g	0.7 pCi/g	0.7 pCi/g
Cs-137	661	84.6	1.093	0.3 pCi/g	0.3 pCi/g	0.3 pCi/g
Am-241[5]	662	0.42	118.5[3]	33.9 nCi/g	35.8 nCi/g	37.2 nCi/g
Am-241	722	0.78	216.6[3]	62.2 nCi/g	65.8 nCi/g	67.9 nCi/g
U-238	1001	0.838	103.4	24.2 pCi/g	25.0 pCi/g	21.9 pCi/g
K-40	1461	10.7	7.802	1.4 pCi/g	1.2 pCi/g	1.4 pCi/g
Natural[6] Thorium	2614	35.8	2.278		0.28[7] pCi/g	

1 - Intensity is the number of gamma rays per 100 decays
2 - Conversion factor from net photo peak count rate (c/s) to radionuclide concentration (pCi/g), includes casing thickness attenuation factor
3 - Conversion factor to nCi/g instead of standard units (pCi/g), for radionuclides with low energy gamma ray
4 - Naturally occurring uranium assumes secular equilibrium with daughter products; Bismuth-214 gamma rays are used to measure radionuclide concentration
5 - ^{241}Am gamma ray (662 keV) conflicts with the ^{137}Cs gamma ray, preventing its use for identifying and quantifying ^{241}Am when ^{137}Cs may be present.
6 - Naturally occuring thorium assumes secular equilibrium with daughter products; the 2614 keV gamma ray of thallium-208 (^{208}Tl) is used to measure thorium concentration
7 – Thorium results calculated from sum of 20 spectra. The 2614 keV photo peak of thorium does not have any interference from other gamma rays and the Compton background is low in this energy region. Therefore the sum of 20 spectra is used to provide a better statistical value for the non-detect limit. This NDL is valid for Overburden as well as the Underburden zones.

The observed differences in the non-detect levels for the three zones shown in the above table are dominated by statistical precision of a 100 second spectra collection time, and are not necessarily representative of changes in the zone condition.

The 662 keV gamma from ^{241}Am can not be used independently to compute the concentrations of ^{241}Am because of possible interference from the ^{137}Cs 661 keV gamma ray, as discussed in Section

5.3.2. Therefore, for the most rigorous identification of ^{241}Am, the non-detect level of the 722 keV gamma ray must be utilized.

5.3.1.2 Minimum Detection Levels

The presence of other radionuclides or more of any given radionuclide increases the Compton background and causes higher MDL than is given above for the non-detect limit. An excellent example is the high count-rate conditions existing in borehole P920 (Pit 9, January 2000). Spectra collected at the maximum survey depth 9.6 ft, where the concentration of the ^{239}Pu and ^{241}Am radionuclides and the hydrogen (2223keV) photo peak are near the lowest encountered in the borehole, yield an MDL for ^{239}Pu of 45 nCi/g, which is 50% greater than the non-detect limit. The logging system dead-time and the total gamma count rate are 3% and 1496 c/s, respectively at this depth (9.6 ft). Also, the observed concentration of ^{239}Pu is 660 nCi/g, which is well above the MDL.

As a second comparison, the spectra collected at 7.5 feet in the same borehole (P920) yield a minimum detection level for ^{239}Pu of 148 nCi/g, which is over three times higher than the MDL two feet lower in the borehole. The logging system dead-time and the total gamma count rate are 24% and 15,455 c/s, respectively, at 7.5 feet which does not exceed the maximum system count rate levels. The observed concentration of ^{239}Pu is thirteen-fold higher at 8800 nCi/g than at 9.6 ft.

5.3.1.3 Maximum System Count Rate

The maximum system count rate is different for borehole surveys acquired after July 2000. The logging system configuration before and after this date are discussed below.

Dead-time occurs for the period of time when the counting system is busy detecting, measuring, and recording a detector signal pulse. Analytical measurements of the logging system (with the manufacturer supplied logging cable; 600 ft) determined that at dead-times of up to 32% (before July 2000) the counting system was linear with radionuclide concentrations, accurately representing the gamma ray flux through which the detector passed, within the measurement uncertainty. As the dead-time increases beyond 32% the linear relationship with radionuclide concentration is not maintained due to the error in the live time clock used for the dead-time correction.

The cause of this variance is the difference between the time required to process each detector signal pulse (which varies with the gamma ray energy, through the long logging cable) and the length of time the system clock is stopped to account for the detector signal pulse processing. The effect on the survey results is that the logging system has a maximum dead-time level (32%) for measuring accurate radionuclide concentration before which the inaccurate electronic dead-time correction becomes a non-negligible factor. Logging system readings above this maximum system count rate level (32% dead-time) are detected and processed, but the measured values are lower than the true concentrations.

The logging system cable was shortened in July 2000 from 600 ft to 100 ft and the signal pulse processing electronics was upgraded to provide optimum performance for the new configuration. Analytical measurements determined that the counting system accurately represented the gamma ray flux (within manufacturer specifications) at dead-times up to 85%.

This improved logging system configuration (logging cable length 100 ft and electronics upgrade) was utilized for the borehole surveys in this project. The spectral-gamma logging system was within the system design limits in each of the RWMC boreholes. No measured values exceeded the maximum allowable dead-time.